The Operation of Vacuum Tubes as Class B and Class C Amplifiers *

By C. E. FAY

A simple theoretical development of the action of a vacuum tube and its associated circuit when used as a Class B or Class C amplifier is given. An expression for the power output is obtained and the conditions for maximum outputs are indicated. The way in which the tuned plate circuit filters out the harmonics in the pulsating plate current wave is illustrated by an hypothetical example. A set of dynamic output current characteristics is developed graphically from a set of static characteristics. The Class B dynamic curves are found to give a better approximation to a straight line than the Class C curves because of a reversed curvature which appears at the lower ends. It is pointed out that the screen grid tube should function similarly to a high μ three-element tube in this type of operation. Experimental dynamic characteristics of a three-element tube, Western Electric 251-A, and of a screen grid tube, Western Electric 278-A, of identical dimensions are shown which verify the theoretical results. The screen grid tube gives about the same output and efficiency as the three-element tube, but its dynamic characteristic tends to bend more rapidly at the upper end.

Introduction

THE majority of modern radio telephone installations in this country are designed for modulation at a low power level and amplification of the modulated carrier, so as to obtain up to 100 per cent modulation in the output stage. As far as the writer is aware there seems to be no very comprehensive material dealing with this phase of vacuum tube operation available from past publications. A treatment of the operation of such amplifiers seems particularly desirable from the standpoint of the design of vacuum tubes for such service.

Some of the fundamental considerations regarding Class B or C operation were given by Morecroft and Friis,[1] and later, a more complete analysis of power oscillators by Prince.[2] Both of these, however, were primarily concerned with the attainment of steady output at high efficiency. Other papers [3, 4, 5] of more recent date have touched somewhat upon the subject.

* To appear in *Proc. I. R. E.*, March, 1932.

[1] J. H. Morecroft and H. T. Friis, "The Vacuum Tube as a Generator of Alternating Current Power," *Transactions A. I. E. E.*, Vol. 38, No. 2, Oct., 1919.

[2] D. C. Prince, "Vacuum Tubes as Power Oscillators," *Proc. I. R. E.*, Vol. 11, Nos. 3, 4, 5, June, Aug., Oct., 1923.

[3] A. A. Oswald and J. C. Schelleng, "Power Amplifiers in Transatlantic Radio Telephony," *Proc. I. R. E.*, Vol. 13, No. 3, June, 1925.

[4] E. E. Spitzer, "Grid Losses in Power Amplifiers," *Proc. I. R. E.*, Vol. 17, No. 6, June, 1929.

[5] Y. Kusunose, "Calculation of Characteristics and the Design of Triodes," *Proc. I. R. E.*, Vol. 17, No. 10, October, 1929.

This paper will deal particularly with the type of amplifier used for the amplification of the modulated carrier. It will be assumed that a linear relation between input voltage and output current is the desired characteristic of such amplifiers and that the more nearly this relation is attained, the less will be the distortion produced.

An approximate graphical method for the calculation of the dynamic output characteristic from the static characteristics of a tube is outlined which is capable of considerable accuracy. The exciting voltage is taken to be a sinusoidal voltage of varying amplitude, and only the fundamental component of the output current is considered. The very important question of the distortion introduced by the nonlinearity of the characteristic and by the resonance effect of the output circuit, as well as the question of the suppression of harmonics in the antenna circuit, is considered to be beyond the scope of this paper.

Theoretical Development

Class B [6] amplifiers have been defined as those which operate with a negative grid bias such that plate current is practically zero with no excitation grid voltage, and in which the power output is proportional to the square of the excitation voltage.

Class C amplifiers have been defined as those which operate with a negative grid bias more than sufficient to reduce the plate current to zero with no excitation grid voltage, and in which the output varies as the square of the plate voltage between limits.

There is actually very little distinction between the two types as the fundamental principles of operation are the same in that the plate current flows in pulses and becomes zero during part of the cycle, the Class C type being merely the case where the duration of the pulses is shorter. For the purposes of this paper, a Class B amplifier shall be regarded as one in which the grid bias is either just sufficient or is not sufficient to reduce the plate current to zero with no excitation grid voltage, and a Class C amplifier as one in which the grid bias is more than sufficient to reduce the plate current to zero with no excitation grid voltage.

Let us consider the plate circuit of a Class B or C amplifier to be represented schematically in Fig. 1. We will omit the grid circuit and assume that the excitation of the grid merely varies the internal tube resistance, R_p, which it does in effect. If at the start, the grid is so biased that no plate current flows, the condenser C_0 will charge up to a potential E_b as indicated in Fig. 1. Let it be assumed that C_0 is of sufficiently large capacity that it presents negligible impedance at the

[6] 1931 Standardization Report, Year Book of the I. R. E., 1931, p. 71.

frequency of operation, or that the time constant of C_0 and R_0 is large compared to the time of one cycle of the operating frequency. In this event, then, the voltage across C_0 will remain constant at E_b during a complete cycle. Let it also be assumed that the choke coil L_b is of sufficient inductance that the current I_b is maintained constant throughout the cycle.

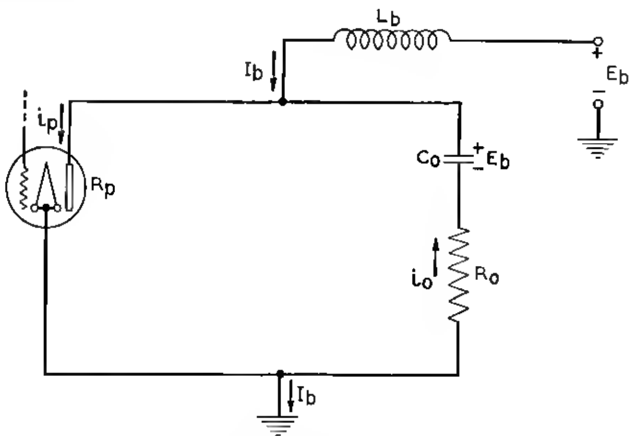

Fig. 1—Schematic of amplifier plate circuit with resistance load.

Then by applying Kirchoff's laws to the circuit, Fig. 1, remembering the assumptions regarding C_0 and L_b, we find the following relations must hold at any instant:

$$E_b = i_p R_p + i_0 R_0 \tag{1}$$

or

$$e_p = E_b - i_0 R_0 \tag{2}$$

and

$$i_0 = i_p - I_b, \tag{3}$$

also

$$I_b = \text{Average of } i_p \text{ over 1 cycle,} \tag{4}$$

since the average current through C_0 must be zero.*

Then let it be assumed that the grid of the tube is excited and biased in such a manner that the plate current, i_p, will vary sinusoidally as illustrated in Fig. 2. When the resistance R_p is at its minimum value, i_p will be a maximum and will be the sum of I_b and i_0, [(1) and (3)]. Also e_p will be a minimum, (2); see point 1, Fig. 2. As R_p is increased by the grid potential going in the negative direction, i_p will be reduced

* See Table of Symbols at end of this paper.

as also will i_0. At the instant when

$$i_p = I_b, \qquad i_0 = 0,$$

as illustrated by point 2, Fig. 2. Then as R_p is further increased, i_p

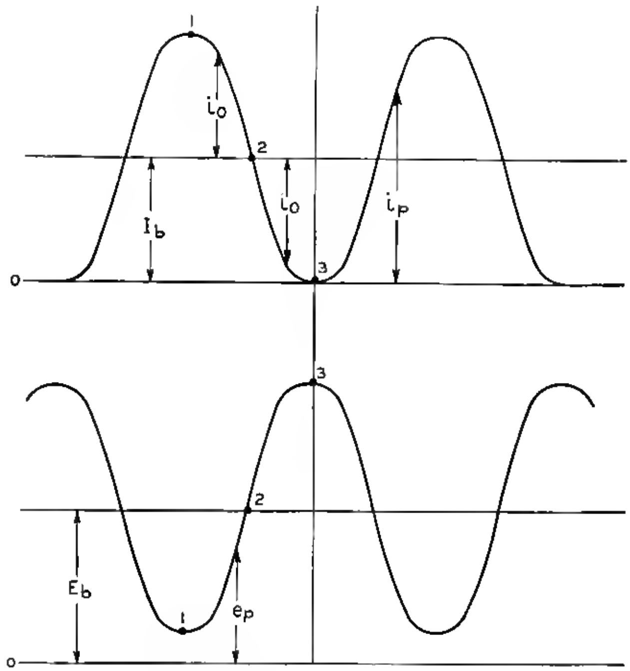

Fig. 2—Plate current and plate voltage relations for sinusoidal plate current in circuit of Fig. 1.

becomes less and i_0 starts to increase in the negative direction until i_p is zero at cut-off;

$$R_p = \infty, \qquad i_0 = -I_b \text{ from (3).}$$

Then from (2) and the above,

$$e_p = E_b + I_b R_0, \tag{5}$$

which is the peak value of e_p. Thus the power in R_0 is $i_0^2 R_0$ averaged over a cycle and the power dissipated in the tube is $i_p^2 R_p$ averaged over a cycle.

In actual operation, the plate current is not sinusoidal but goes from zero to peak value and back to zero in about half the cycle and remains

cut off during the rest of the cycle, as illustrated by Fig. 4A. Also, instead of being a pure resistance, the output circuit consists of a tuned tank circuit, Fig. 3, into which resistance is introduced either directly or by coupling in some way. Thus the impedance of the output circuit will be a resistance to the fundamental frequency only. However, the same general principles will apply in this case as in the case

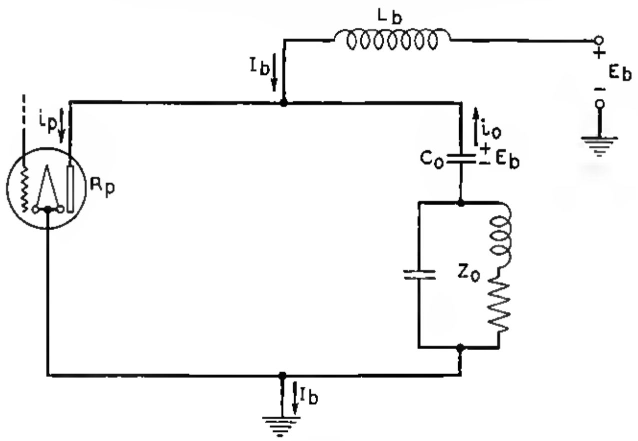

Fig. 3—Schematic of amplifier plate circuit with tuned output impedance.

of the sinusoidal plate current and the pure resistance circuit. The equations will be of the same form except that Z_0 must be substituted for R_0 as follows:

$$E_b = i_p R_p + i_0 Z_0, \tag{1A}$$

$$e_p = E_b - i_0 Z_0, \tag{2A}$$

$$i_0 = i_p - I_b, \tag{3}$$

$$I_b = \text{Average of } i_p \text{ over 1 cycle.} \tag{4}$$

In this case it must be remembered that the wave of i_p, and hence i_0, instead of being a simple sine wave, is a more complex wave consisting of a fundamental frequency and numerous harmonics. Also $i_0 Z_0$ is the sum of all such components multiplied by the respective impedances presented to them taken in their proper phases.

Considering the wave form of i_0 shown in Fig. 4B, which is readily obtainable in practice, it should be evident from inspection that it can be considered a cosine wave containing odd and even cosine terms and may be expressed by

$$i_0 = I_1 \cos \omega t + I_2 \cos 2\omega t + I_3 \cos 3\omega t + I_4 \cos 4\omega t + \cdots + I_n \cos n\omega t.$$

By means of an harmonic analysis of this wave for the numerical values indicated in Fig. 4B, the coefficients were found to be approximately as follows:

$$I_1 = 0.96, \quad I_2 = 0.543, \quad I_3 = 0.140, \quad I_4 = -0.07, \quad I_5 = -0.105, \quad I_6 = -0.043.$$

The voltage produced across the output circuit by the wave, i_0, then will be the sum of the voltages produced by each one of the com-

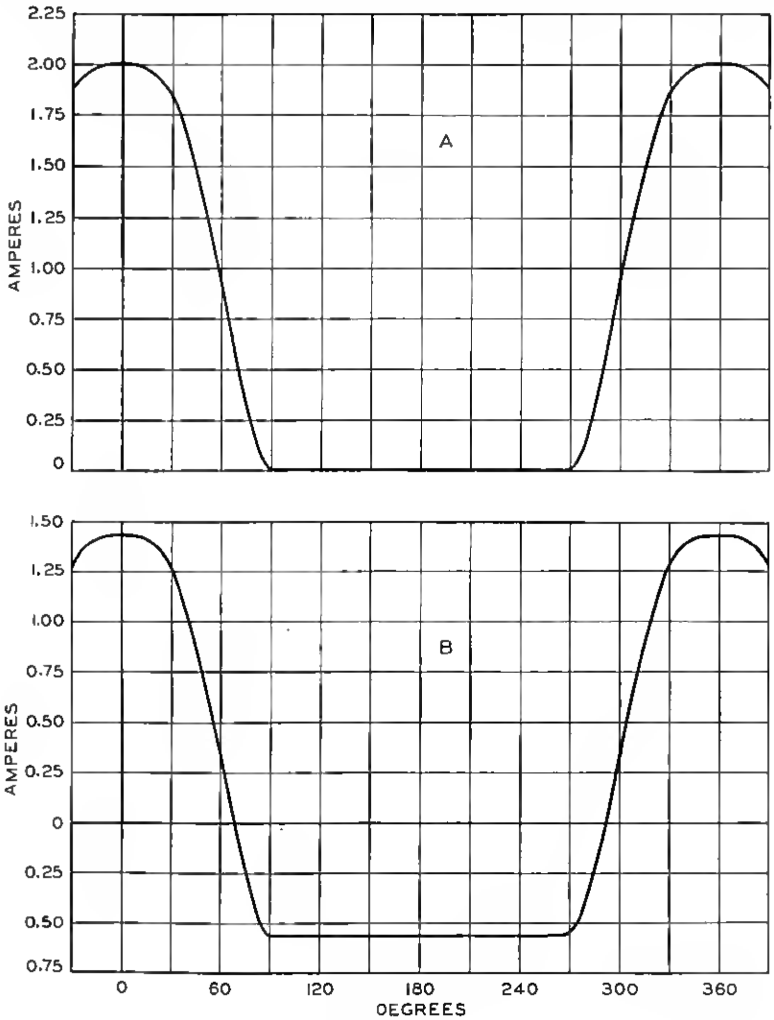

Fig. 4—*A*. Pulsating plate current wave, i_p. *B*. Alternating component of plate current, i_0.

ponents of i_0. Let it be assumed that the reactances of the output circuit are 300 ohms each at fundamental frequency and that sufficient resistance has been inserted in the inductive branch to make the impedance to fundamental frequency 2000 ohms resistance. This will require about 45 ohms in series with the inductance. At second harmonic frequency, then, the impedance of the inductive branch in complex notation is $45 + j600$ and that of the capacity branch $0 - j150$. Without introducing much error in the result we may as well write $+ j600$ and $- j150$, which in parallel give $- j200$. At third harmonic frequency we have $+ j900$ and $- j100$ which in parallel give $- j112.5$. At fourth harmonic frequency we have $+ j1200$ and $- j75$ which in parallel give $- j80$.

Thus the voltage produced by the fundamental will be

$$e_1 = 0.96 \times 2000 \cos \omega t = 1920 \cos \omega t,$$

and that produced by the second harmonic will be

$$e_2 = 0.54 \times 200 \cos (2\omega t - 90°) = 108 \cos (2\omega t - 90°),$$

and that produced by the third harmonic will be

$$e_3 = 0.14 \times 112.5 \cos (3\omega t - 90°) = 15.75 \cos (3\omega t - 90°),$$

and that produced by the fourth harmonic will be

$$e_4 = - 0.07 \times 80 \cos (4\omega t - 90°) = 5.6 \cos (4\omega t + 90°),$$

etc. Fig. 5B shows to scale the fundamental and second harmonic voltages produced, and the dotted curve gives the sum. The higher harmonic voltages are too small to show on the plot. The resultant is seen to be very little different from a sine wave. Therefore, even though the wave i_0 departs radically from a sine wave, the voltage produced across the output circuit is very nearly sinusoidal. Then the output power at fundamental frequency is

$$W_0 = \frac{I_1^2 R_0}{2}, \tag{6}$$

where I_1 is the peak value of the fundamental component of i_0, and R_0 is the effective resistance of the tank circuit at fundamental frequency.

The output power may also be expressed:

$$W_0 = \frac{(E_b - e_{pm}) K I_p}{2} \tag{7}$$

if $I_1 = KI_p$.

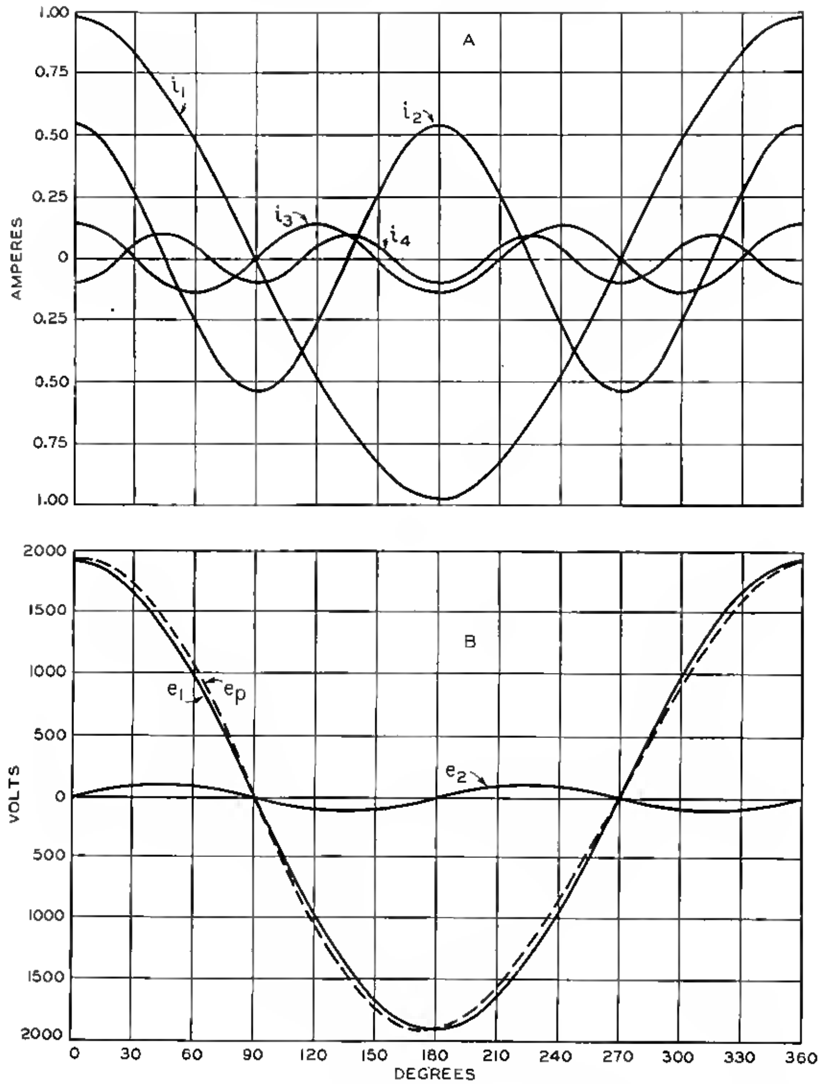

Fig. 5—*A*. First four components of i_0, Fig. 4*B*. *B*. Alternating components of plate voltage produced by i_0 in output circuit.

For any constant value of grid voltage, the plate current will be some function of the plate voltage, so that for any peak value of e_g we may write

$$e_{pm} = f(I_p). \tag{8}$$

Substituting (8) in (7) we have

$$W_0 = \frac{[E_b - f(I_p)]KI_p}{2}. \tag{9}$$

In order for W_0 to be a maximum,

$$\frac{dW_0}{dI_p} = 0.$$

Performing this operation on (9) and solving for I_p assuming K is constant, we get

$$I_p = \frac{E_b - f(I_p)}{f'(I_p)} = \frac{E_b - e_{pm}}{r_p} \tag{10}$$

since $f'(I_p)$ is $df(I_p)/dI_p$, which is obviously r_p, the differential plate resistance when I_p is flowing.

We may also write

$$R_0 = \frac{E_b - e_{pm}}{KI_p}. \tag{11}$$

Substituting (10) in (11) we obtain

$$R_0 = \frac{r_p}{K} \tag{12}$$

which gives the relation of R_0 to r_p for maximum power output.

If we have the $i_p - e_p$ curves for any tube we may approximate closely the point of maximum output at any peak grid voltage. This can be accomplished by a process of cut and try in finding where the quantity $(E_b - e_{pm})I_p$ becomes a maximum, since K remains fairly constant, depending mostly on the bias voltage and grid excitation voltage, as will be shown later. Also, for any given output impedance and peak grid voltage, we may find the output from the $i_p - e_p$ curves by cut and try by finding where

$$\frac{E_b - e_{pm}}{I_p} = KR_0 \qquad \text{[from (11)]}$$

is satisfied. It will be noticed from Figs. 4A and 5A that $I_1/I_p = 0.48$. In general, K will be near this value for well loaded conditions. The actual value depends upon the exciting voltage and grid bias voltage, and at low values of excitation it may differ considerably from the value indicated above which may render the cut and try methods outlined subject to considerable error.

In addition to finding the maximum output for a given set of con-

ditions it is desirable to know what the shape of the curve of output current versus exciting voltage will be. The following method determines points on the output curve by the use of the static characteristic of the tube.

In Fig. 6 is shown a family of plate current curves obtained by applying a sine wave grid voltage to a three-halves power characteristic with a plate voltage consisting of a steady voltage plus a sine wave 180° out of phase with the grid voltage. The different curves show the relative shapes obtained by variation of the grid bias so that the portion of the cycle during which plate current flows is varied. It can

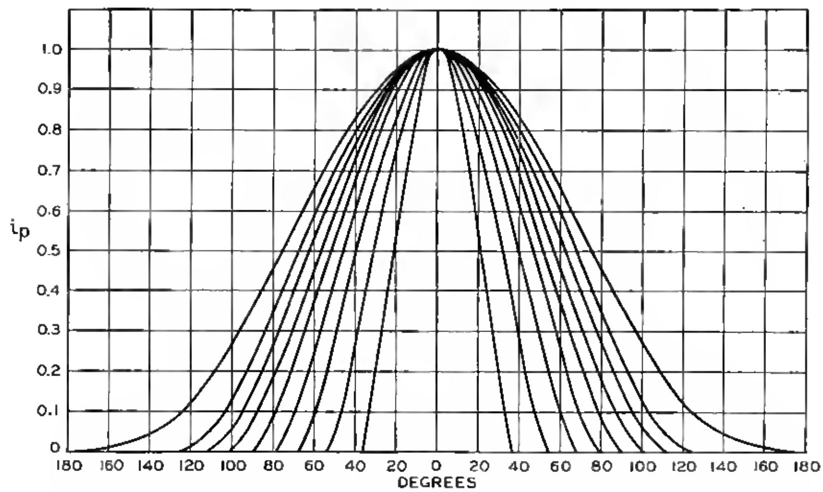

Fig. 6—Curves of i_p obtained from a three halves power characteristic with sinusoidal exciting voltage for varying periods of plate current flow.

be shown that for any tube, no matter what the actual values of voltages and currents are, as long as the portion of the characteristic under consideration obeys the three-halves power law, the plate current waves will correspond to those of Fig. 6 in shape for the same respective periods of plate current flow. By means of harmonic analyses, the value of K corresponding to each of these shapes was calculated and Fig. 7 shows the variation of K with the number of degrees during which plate current flows. Fig. 8 shows a comparison of three possible shapes for 180° flow with the corresponding values of K. A is the unsaturated curve of Fig. 6. B shows a curve for which the characteristic departs from the three-halves power law at its upper end, presumably due to the effects of grid current, etc. This curve if unsaturated would have a peak value about 17 per cent higher. C shows

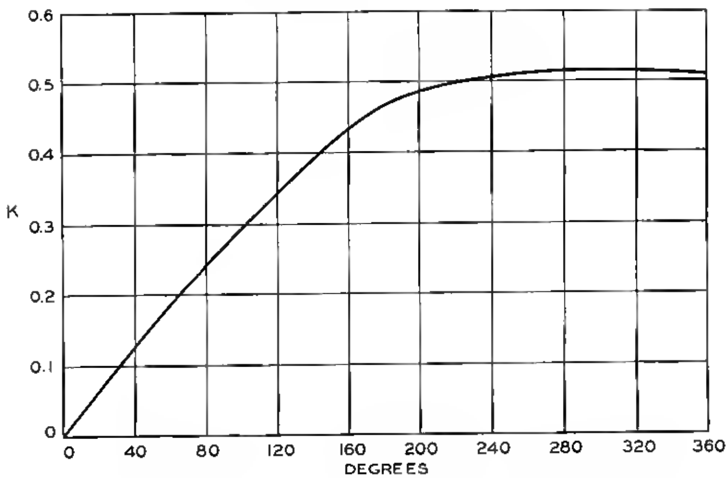

Fig. 7—Variation of K with period of flow for curves of Fig. 6.

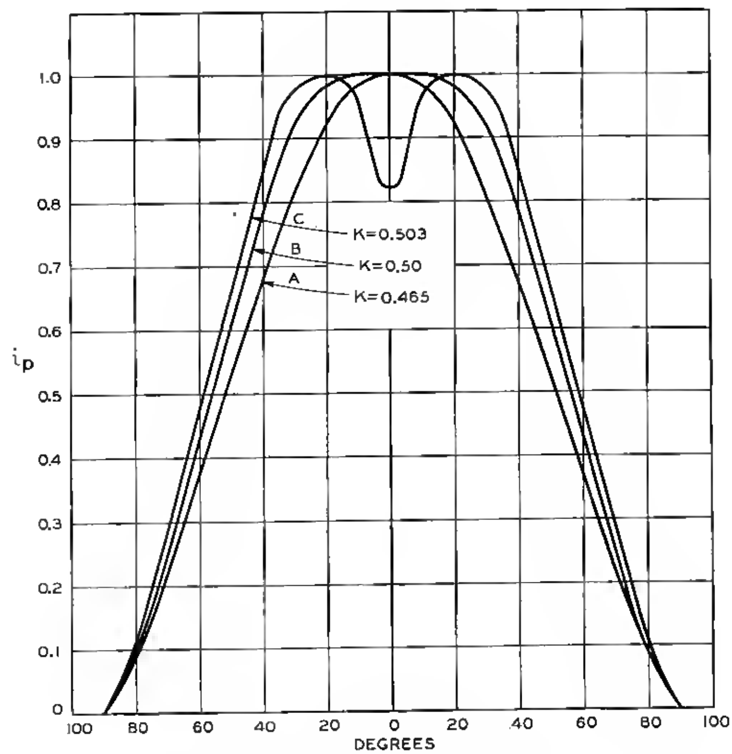

Fig. 8—Three typical shapes of plate current for 180° flow. A, unsaturated. B, slightly saturated. C, extremely saturated.

a curve for which the saturation is so pronounced that the grid current drawn has caused a depression.

In actual tubes the static characteristics do not follow the three-halves power law exactly, but for the purposes of this paper it is sufficiently accurate to assume that they do in the portion where grid current is not appreciable.

With the information available from Figs. 6 and 7, and the static characteristic of a tube, we should be able to plot the dynamic characteristic for any value of output impedance. For an example, let Fig. 9 represent the static characteristics of a tube (Western Electric

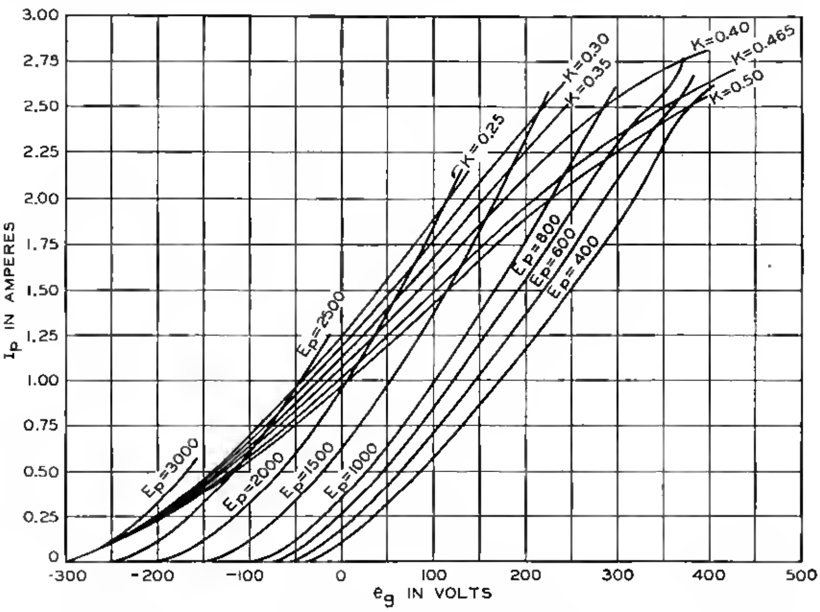

Fig. 9—Static characteristic with lines of constant K for 2000 ohms impedance. (Western Electric No. 251-*A* Tube.)

No. 251-A). Then for some value of output impedance, say 2000 ohms, let us plot curves of constant K on the static characteristic assuming $E_b = 3000$ volts. Points on these curves are found from

$$I_p = \frac{E_b - e_{pm}}{KR_0},$$

which is another form of (11). For example, to find where the $K = 0.5$ curve crosses the $E_p = 2000$ curve, we have $e_{pm} = E_p = 2000$, $E_b - e_{pm} = 1000$, thus

$$I_p = \frac{1000}{0.5 \times 2000} = 1.0 \qquad \text{(Fig. 9).}$$

The cut-off point, or the potential which the grid must have to make the plate current just zero is given by

$$e_g \text{ cut-off} = -\frac{E_b}{\mu}. \tag{13}$$

If we bias the grid with this negative voltage, it may be said to be biased at cut-off, and if the grid voltage becomes more positive than this value, plate current will flow. Thus if we apply a sinusoidal exciting voltage, the plate current will always flow during 180°, or half the cycle, and for this condition $K = 0.465$ from Fig. 7, so the dynamic output current curve will be obtained by multiplying the ordinates of the $K = 0.465$ curve of Fig. 9, by 0.465. However, in the upper portion where the static characteristics depart appreciably from the three-halves power law, K will increase gradually (Fig. 8), so that it is more accurate to use slightly increasing values of K in this portion. (See table of calculations for $E_c = 300$, Fig. 10.)

$E_b = 3000$ Volts $\qquad$ $Z_0 = 2000$ ohms

E_c Volts	Peak Excitation Volts	Peak e_g Volts	K	I_p Amp.	I_1 Amp.	$\frac{I_1}{\sqrt{2}}$ Amp.	Watts Output $\left(\frac{I_1}{\sqrt{2}}\right)^2 Z_0$	Output Current in 150 ohm Ant. Amp.
−300	100	−200	0.465	0.230	0.107	0.0756	11.5	0.276
	200	−100	0.465	0.575	0.267	0.1885	71	0.688
	300	0	0.465	1.01	0.47	0.332	222	1.218
	400	+100	0.465	1.49	0.692	0.490	480	1.790
	500	200	0.47	1.95	0.917	0.647	840	2.37
	600	300	0.48	2.30	1.07	0.756	1150	2.96
	650	350	0.49	2.45	1.20	0.848	1440	3.10
−350	100	−250	0.345	0.112	0.039	0.027	1.49	0.099
	200	−150	0.415	0.410	0.170	0.122	28.9	0.438
	300	− 50	0.435	0.810	0.352	0.249	124	0.907
	400	+ 50	0.445	1.280	0.570	0.403	324	1.470
	500	150	0.45	1.77	0.797	0.563	635	2.055
	600	250	0.452	2.20	0.995	0.702	988	2.56
	650	300	0.453	2.40	1.087	0.768	1180	2.80
−250	50	−200	0.51	0.220	0.112	0.079	12.6	0.290
	100	−150	0.505	0.375	0.190	0.134	36	0.490
	200	− 50	0.492	0.760	0.374	0.265	140	0.966
	300	+ 50	0.483	1.220	0.590	0.417	348	1.525
	400	150	0.480	1.710	0.820	0.580	674	2.120
	500	250	0.477	2.137	1.020	0.721	1040	2.635
	600	350	0.475	2.475	1.173	0.830	1380	3.030

Fig. 10—Calculation of dynamic output characteristics—No. 251-A tube.

If the grid bias is more negative than the cut-off point (i.e., if the tube is biased "below cut-off"), the plate current will not begin to flow until the grid potential has reached the cut-off point (13), and

the portion of the cycle in which plate current flows will be determined by the number of degrees of the cycle in which the exciting wave is above the cut-off point. Thus in this case, K will depend on the amplitude of the exciting wave compared to the difference between the bias and the cut-off point. When the amplitude becomes large compared to this difference, the period of plate current flow approaches 180° but when the peak value of the exciting wave just reaches the cut-off point, the period of flow is zero. In this case K can vary from almost 0.465 to zero depending on the amplitude of the exciting wave, or if the exciting voltage is sufficient to produce a saturation effect in the plate current wave, K might exceed 0.465. This is the case of the Class C amplifier.

If the grid bias is more positive than the cut-off point (i.e., if the tube is biased "above cut-off"), plate current flows during 360° of the cycle until the amplitude of the exciting voltage is sufficient to reach the cut-off point. The period of flow continues to decrease until it approaches 180° as the amplitude of the exciting voltage becomes large compared to the difference between the bias and cut-off potentials. Here K is always greater than 0.465; see Fig. 7. This is the case of the Class B amplifier.

Fig. 10 outlines the calculation of dynamic characteristics of both types from the static characteristics of Fig. 9. In these calculations, the cut-off point is assumed to be constant at -300 volts and the value of K is obtained from Fig. 7 after determining the portion of the cycle in which the exciting voltage is above the cut-off point. For $E_c = -300$ of course it is always 180°. For $E_c = -350$, and a peak exciting voltage of 100 volts for example, the peak e_g will be -250 which will give 120° for the period of flow and thus $K = 0.345$ from Fig. 7. Then on the static characteristic, Fig. 9, taking $e_g = -250$, and by interpolating between the $K = 0.30$ and $K = 0.35$ curves to $K = 0.345$ we find $I_p = 0.112$. Multiplying this by K we get $I_1 = 0.0386$. Changing to r.m.s. value, squaring and multiplying by 2000 ohms, we obtain 1.49 watts for the output power. It is then determined that this would represent a current of 0.0995 ampere in the 150-ohm dummy antenna which was used in the experimental work, and which was so coupled to the output tank circuit that the impedance into which the tube was working was of the value indicated.

In the calculations of Fig. 10, the cut-off point was assumed constant at $-E_b/\mu$. However, it actually varies as $-e_p/\mu$ and will vary sinusoidally if e_p is sinusoidal. No error is introduced by this fact in the case of bias at cut-off ($E_c = -300$). However, in the other two cases an error is introduced. In the case for bias below

cut-off ($E_c = -350$) the amount of error is indicated by the two points illustrated in Fig. 11. *A* is the case for a peak exciting voltage of 300 volts. From the static characteristics of Fig. 9 we find that e_{pm} will be about 2300 volts which will make -230 volts, the peak of the real cut-off curve ($-e_p/\mu$) and since it is a sine wave we can plot

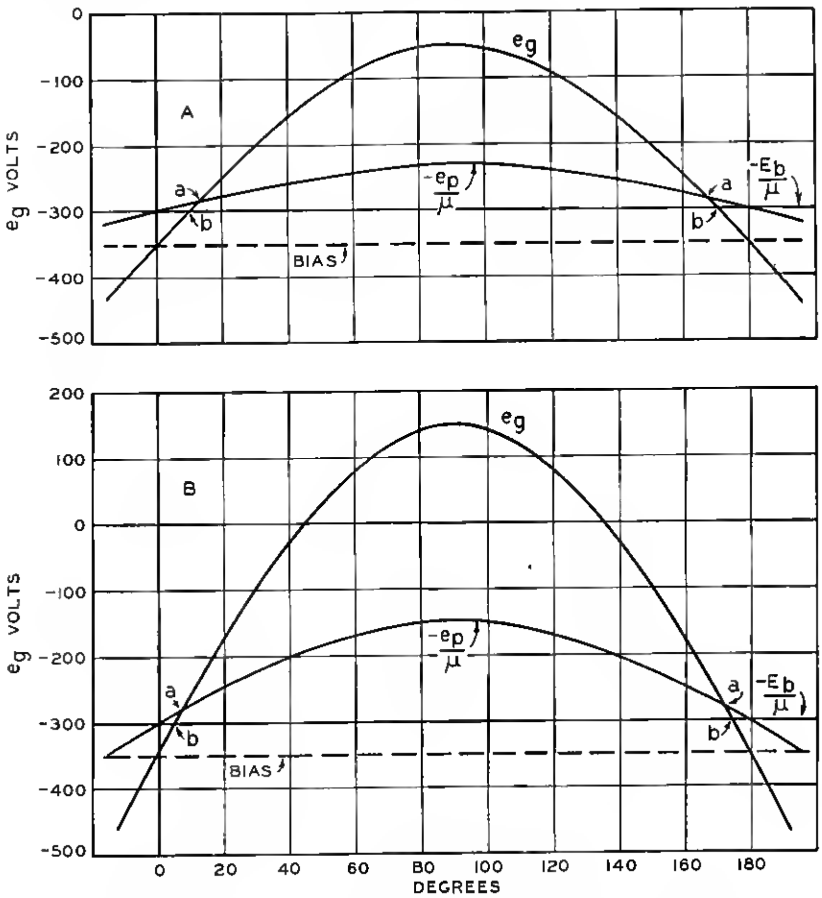

Fig. 11—Illustrating method of obtaining actual period of flow of plate current. *a*, acutal cut-off point, *b*, cut-off point assumed in calculations.

it as shown. The error in the period of flow then will be represented by the difference between where the e_g curve cuts the $-$ 300-volt line and where it cuts the $-e_p/\mu$ curve. The actual period of flow is about 156° instead of 160° as found before, which would make $K = 0.425$ instead of 0.435. *B* is the case for a peak exciting voltage of

500 volts and by the same procedure we find $K = 0.441$ instead of $K = 0.45$. These errors are quite small and do not alter the result appreciably in these cases.

The effect will be less pronounced, the higher the μ of the tube, and more pronounced the further the bias voltage is moved from the cut-

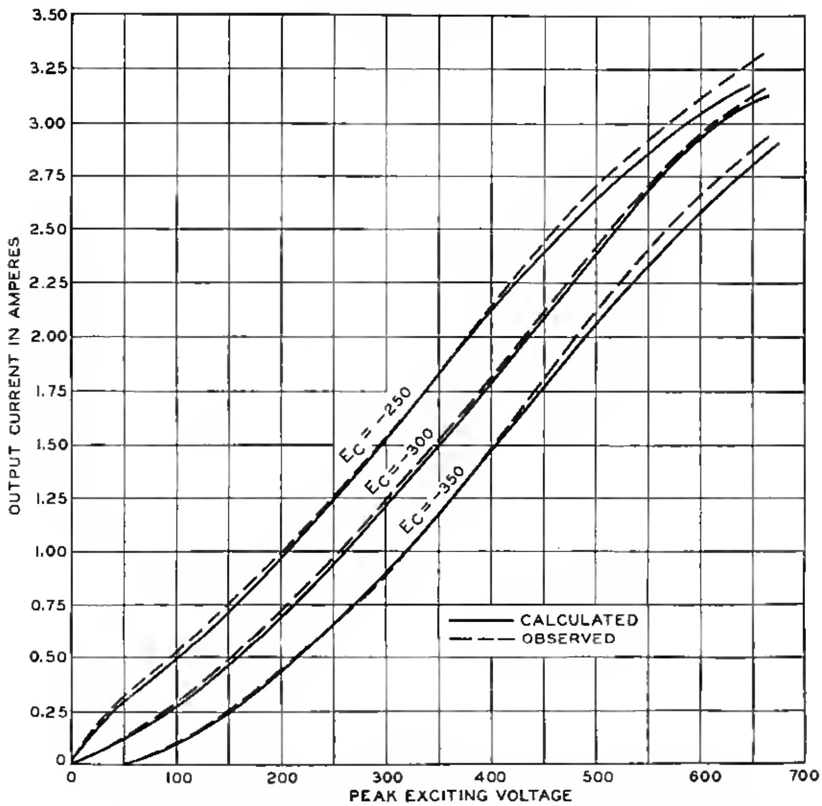

Fig. 12—Calculated and experimental dynamic characteristics of Western Electric No. 251-*A* Tube $E_b = 3000$ volts, $Z_0 = 2000$ ohms, $\mu = 10$.

off point. For extreme cases in which more accuracy is desired, K will be determined quite accurately by the second approximation method of Fig. 11. For the case of bias above cut-off where K is always greater than 0.465 the error in determining K will be considerably smaller as K does not vary greatly with the period of flow in this region; see Fig. 7. In the upper portion of the characteristic where departure from the three halves power law becomes appreciable, the increase in K due to this saturation effect which must be estimated,

Fig. 8, may be greater than the error produced by neglecting the varying cut-off. In this event it would hardly be worthwhile to use the method of Fig. 11, except in extreme cases where the bias differs greatly from the cut-off potential.

The dynamic output current characteristics calculated in Fig. 10 are shown plotted to scale in Fig. 12. It should be noted that for the case of bias above cut-off ($E_c = -250$) the curvature of the dynamic is reversed at the lower end. This will tend to allow a better approximation to a straight line for the overall curve than can be obtained for curves of bias below cut-off.

In general the highest output impedance admissible will give the straightest dynamic curve for a given tube. Comparing two tubes of equal power rating, the one with the highest mutual conductance will give the straightest dynamic characteristic with a given output impedance.

It will be noticed that the dynamic curves tend to show a saturation effect at their upper ends. This is predicted, however, from the static characteristics. If the grid excitation voltage is sufficient to allow the grid potential to approach the plate potential very closely, the electron current taken by the grid will increase rapidly. Since this current taken by the grid would otherwise have been taken by the plate, the result is a reduction in the value of i_p which causes the plate current characteristic to depart from the three-halves power law. A slight saturation effect at the upper end of the dynamic curve may help the curve to approximate a straight line more closely. The output impedance may be chosen so as to realize this advantage provided the grid becomes positive during a sufficient portion of the cycle.

The Screen Grid Tube

The foregoing theory, with a few alterations, will apply equally well to the screen grid tube. In any screen grid tube where the screening is sufficient to reduce the grid-plate capacity to the point where operation at high frequencies without neutralization is feasible, the screen voltage will determine the plate current at a given grid voltage almost entirely, the plate voltage having very little effect. In this case the cut-off point will be given approximately by

$$e_g \text{ cut-off} = -\frac{E_s}{\mu}, \tag{14}$$

where μ here is the μ of a three-element tube with the plate in place of the screen. A more exact formula would be

$$e_g \text{ cut-off} = -\frac{E_b + \rho E_s}{\mu(1 + \rho)}, \tag{15}$$

where μ is as defined above, and ρ is the amplification factor of a three-element tube considering the screen as the grid. However, if ρ is large compared to μ and μ is greater than 1, the cut-off point is given quite closely by (14).

In operation the screen is by-passed to ground by a large capacity so that the screen potential will remain practically constant at E_s to insure the effectiveness of the screening action. As the minimum plate potential approaches the screen potential, the screen will begin to draw appreciable current and thus cause a saturation effect in the characteristic similar to that of the three-element tube when the minimum plate potential approaches the maximum grid potential. Also, as the maximum grid potential approaches the screen potential, the grid will begin to draw current which will subtract from the plate and screen currents, thus tending also to cause a saturation effect in the characteristic. It would seem desirable, therefore, that the screen voltage be chosen somewhere between the maximum grid potential and the minimum plate potential, the actual point depending on whether grid current or screen current is the least desirable. In operation the screen grid tube should give the same type of characteristics as indicated in Fig. 12 and have some advantage from the fact that as a high μ tube it requires less driving voltage. However, the dynamic characteristic may tend to saturate sooner than it would for the equivalent three-element tube because of the tendency of both the screen and the grid to absorb current under the conditions mentioned above.

Experimental Results

In Fig. 12 along with the curves calculated from the theoretical development are shown the actual experimental curves obtained at 3000 kc for the same conditions.

The following dynamic output current and efficiency curves of the three-element tube, Western Electric 251-A, and the screen grid tube, Western Electric 278-A, measured at 3000 kc are submitted to show the effects of various factors on the dynamic characteristic. They allow a direct comparison of the three-element tube and the screen grid tube.

The curves of Fig. 13 show the dynamic output currents and efficiencies obtained from the three element tube for the conditions indicated. The upper portions of these curves show some saturation effect and they are practically identical except that they are displaced along the abscissa by approximately the differences in grid bias. Fig. 14 shows the effect of varying the output impedance for the case of bias

at cut-off. The relative effect for other biases is practically the same as for the case shown.

Fig. 15 shows the dynamic output currents and efficiencies for a

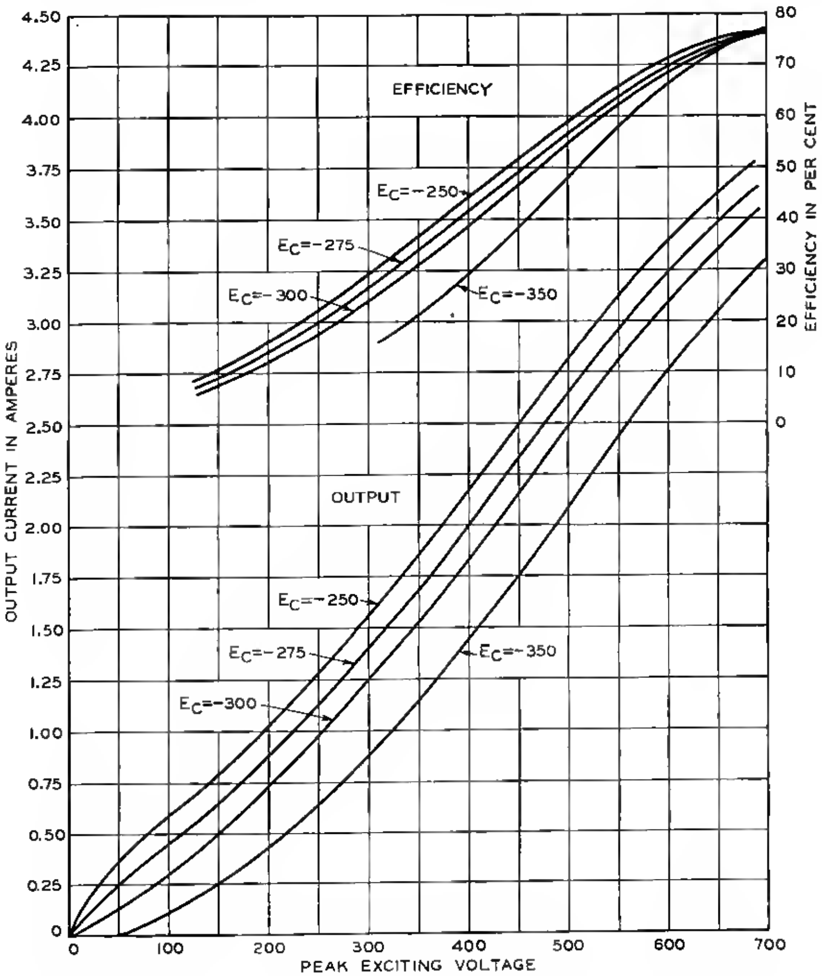

Fig. 13—Dynamic output and efficiency of a three-element tube. $E_b = 3000$ volts, $\mu = 10$, $Z_0 = 1500$ ohms.

screen grid tube which is identical in construction with the three-element tube except for the addition of the screen between the grid and plate. The μ of this tube considering the screen to be the plate is about 4, so that the cut-off bias is about $-E_s/4$. The curves of

Fig. 15 were taken with the screen voltage and output impedance constant at 400 volts and 1500 ohms respectively. It will be noted that these curves show the same general characteristics at the lower portions as the curves of the three-element tube, Fig. 13, but as predicted in the theoretical consideration, they tend to saturate more rapidly

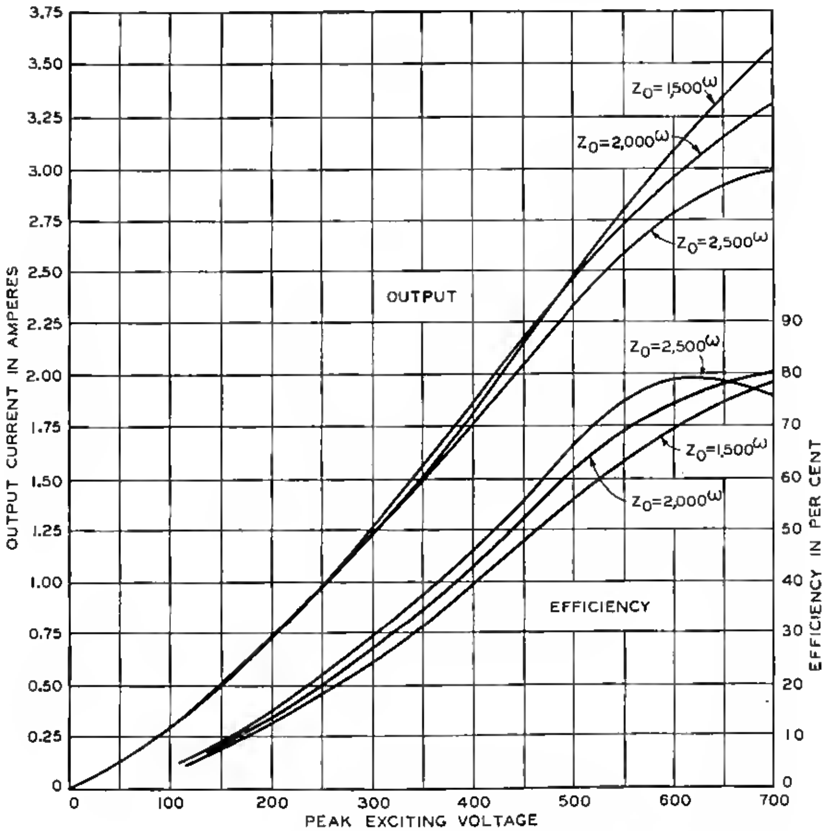

Fig. 14—Dynamic output and efficiency of a three-element tube. $E_b = 3000$ volts, $E_c = -300$ volts, $\mu = 10$.

in the upper portion. The efficiencies appear to be about the same as obtainable from the three-element tube at the same outputs.

Fig. 16 shows a comparison of the dynamic output curves at 1500 ohms impedance and bias at cut-off of the screen grid tube for three different values of screen voltage, and of the three-element tube. In addition the d-c. screen currents and grid currents are shown. The

high μ effect of the screen grid tube is responsible for the steeper dynamic curve. The reason for the greater saturation effect at the upper portion of the curves for the screen grid tube is apparent upon com-

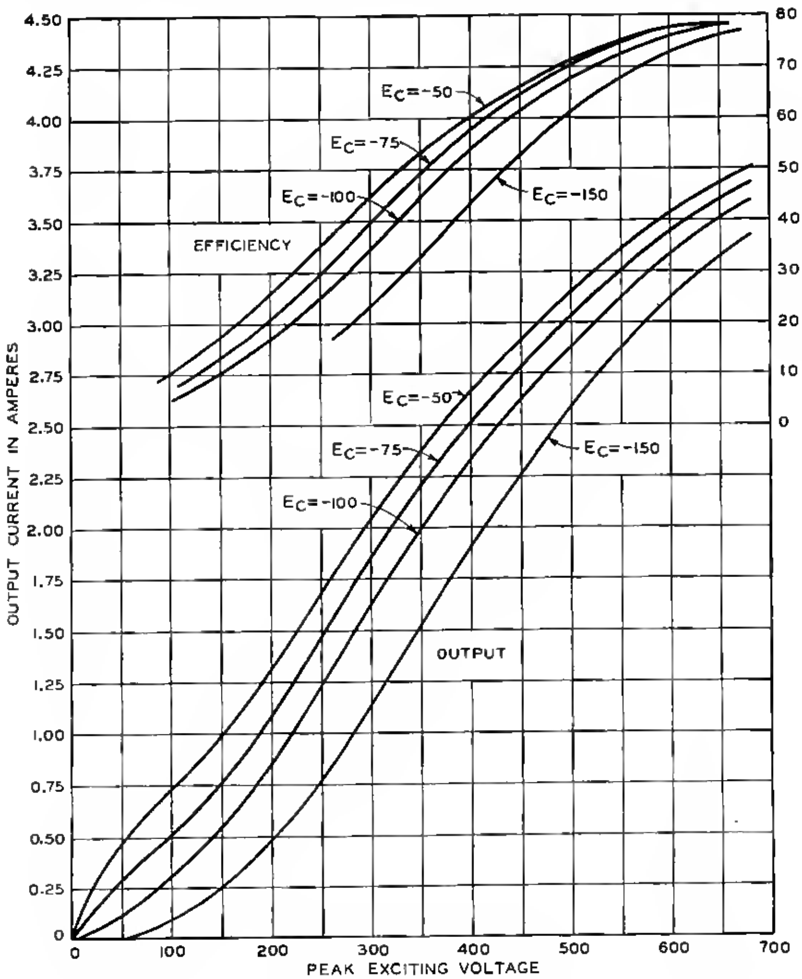

Fig. 15—Dynamic output and efficiency of a screen grid tube. $E_b = 3000$ volts, $E_s = 400$ volts, $Z_0 = 1500$ ohms.

paring the d-c. screen and grid currents with the grid current for the three-element tube, since the plate is being robbed of the current taken by grid and screen in one case, and only of the current taken by the grid in the other. In Fig. 17, the effect of the output impedance on

the screen grid dynamic curves is shown. The effect is seen to be similar to that for the three-element tube, though somewhat more pronounced.

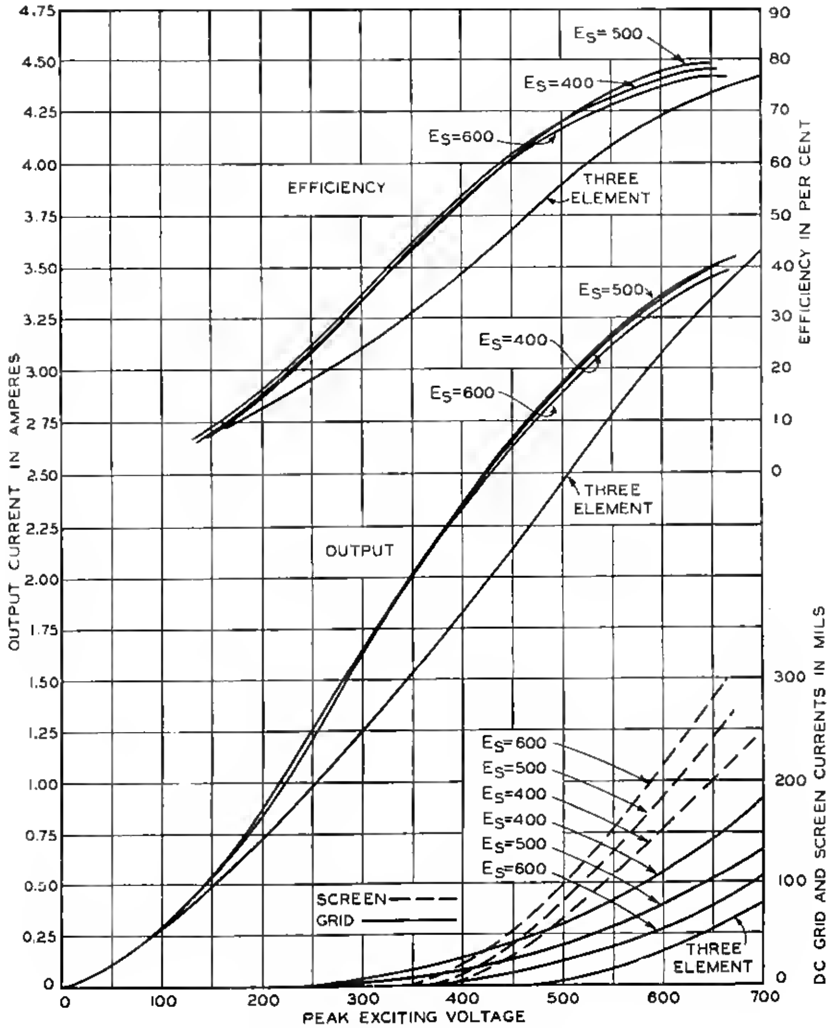

Fig. 16—Dynamic output and efficiency of a screen grid tube compared to that of a three-element tube. $E_b = 3000$ volts, E_c at cut-off $Z_0 = 1500$ ohms.

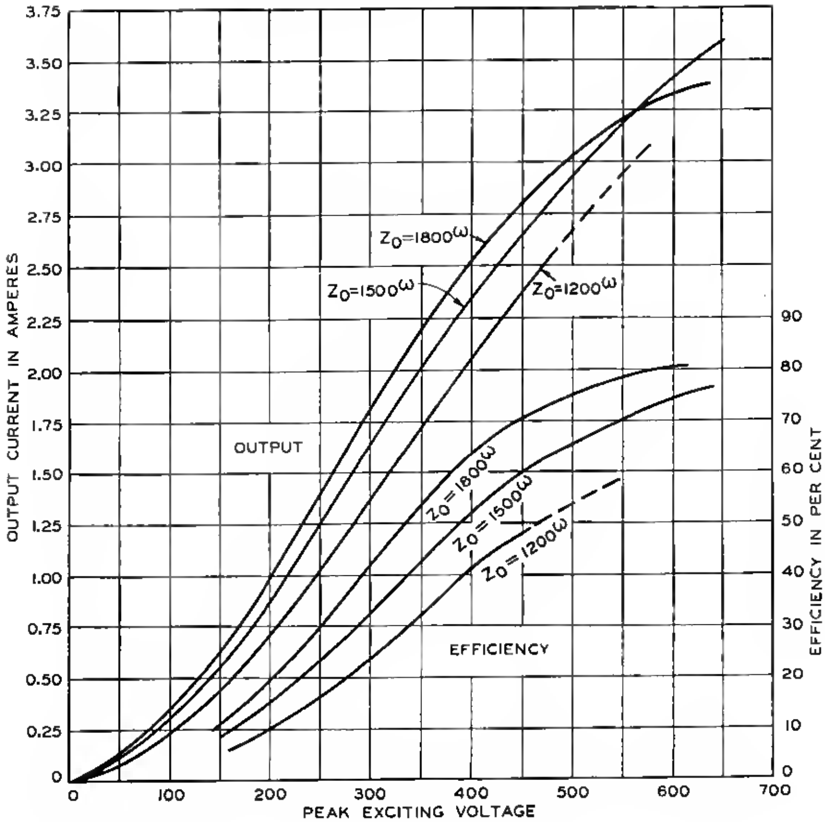

Fig. 17—Dynamic output and efficiency of a screen grid tube. $E_b = 3000$ volts, $E_c = -100$, $E_s = 400$ volts.

Conclusions

It has been shown from both theory and experiment that there is a marked difference between the dynamic output characteristics of Class B and Class C amplifiers as defined, particularly in the lower portion of the curves. This difference is the more pronounced the farther the grid bias voltage is moved from the cut-off point. In general, Class C operation is more efficient than Class B operation because the flow of plate current is limited to a smaller portion of the cycle which includes the portion in which the plate voltage is lowest.

It must be borne in mind that in a radio telephone transmitter where modulation is effected at low power level and the modulated carrier amplified, the dynamic characteristic of the output current will be the resultant of the dynamic characteristics of all of the intermediate

stages from the modulating stage through the final amplifier stage. In certain cases distortion in one stage might be fairly well compensated for by suitably shaping the characteristic of the following stage through choosing proper values of bias voltage and output impedance.

It may be concluded from both theory and experiment that the screen grid tube functions in general similarly to the three-element tube and is capable of giving about the same output efficiency. It possesses the property of the high μ tube in giving greater output for a given exciting voltage in the portion of the dynamic characteristic where saturation has not become noticeable, but the dynamic characteristic shows saturation much sooner than that of the three-element tube. The screen grid tube also has the property that the output impedance has very little effect on the input circuit which will allow some shaping of the dynamic characteristic without affecting the driving power.

The fact should be mentioned that the so-called internal impedance, or plate impedance of the tube, such as might be measured on a bridge for small amplitudes of plate current swing, bears no very close relation to the impedance of the output circuit into which it should work in Class B or Class C operation. Reference to this plate impedance is quite misleading unless the part of the characteristic from which it is taken is given, since it varies greatly over the characteristic. For the screen grid tube mentioned the internal plate impedance is of the order of 100,000 ohms, whereas it was working with an output impedance of the order of 1500 ohms.

Table of Symbols

E_b = d-c. plate voltage

E_c = d-c. grid voltage

E_s = screen grid voltage (held constant)

e_p = instantaneous plate potential

e_g = instantaneous grid potential

e_{pm} = minimum plate potential

e_1 = instantaneous value of fundamental frequency component of alternating plate voltage

e_n = instantaneous value of n^{th} harmonic component of alternating plate voltage

I_b = d-c. plate current

I_p = peak value of plate current

i_p = instantaneous value of plate current

i_0 = instantaneous value of alternating component of plate current

i_1 = instantaneous value of fundamental frequency component of alternating plate current

i_n = instantaneous value of n^{th} harmonic component of alternating plate current

I_1 = peak value of fundamental frequency component of alternating plate current

I_n = peak value of n^{th} harmonic component of alternating plate current

μ = amplification factor of tube = $\left[\dfrac{\Delta e_p}{\Delta e_g}\right]_{i_p \text{ constant}}$

K = I_1/I_p

W_0 = power output in watts

Z_0 = output impedance = R_0, a resistance at fundamental frequency

R_p = instantaneous internal resistance of the tube

r_p = differential plate resistance of tube at any point

$$= \left[\frac{\Delta e_p}{\Delta i_p}\right]_{e_g \text{ constant}}$$